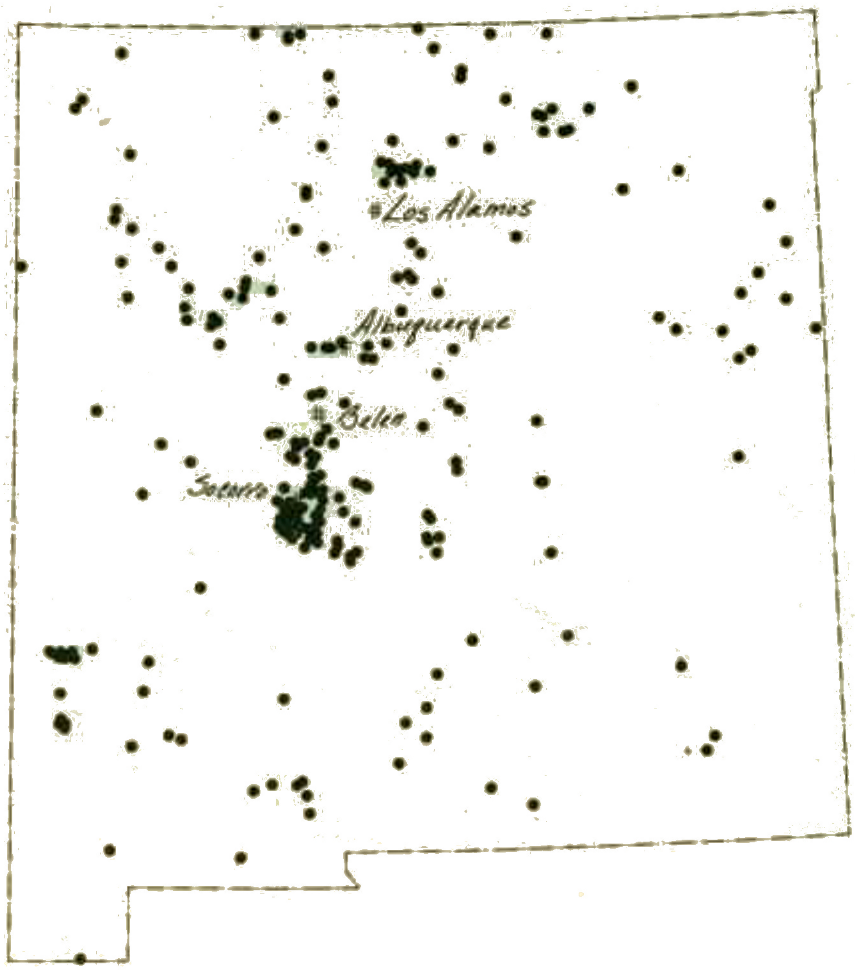
Earthquakes in New Mexico, 1849-1977

by
Allan R. Sanford,
Kenneth H. Olsen,
and Lawrence **H.** Jaksha



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Preface

Groups at New Mexico Institute of Mining and Technology, Los Alamos Scientific Laboratory, and the U.S. Geological Survey's Albuquerque Seismological Laboratory have been engaged in instrumental studies of the seismicity of New Mexico for several years. This report collates and reconciles differences in data obtained by all three organizations for the period 1962-1977. Tabulated in the paper are located shocks whose magnitudes are equal to or greater than 1.5. Procedures for locating earthquakes and calculating magnitudes are given. Preceding the presentation of instrumental data is a tabulation and discussion of historical reports of earthquakes dating from 1849.

Estimates of the level of seismicity based on the instrumental data are presented and compared with historical data on New Mexico shocks and the intensity of earthquake activity in southern California. Finally, the distribution and strength of earthquake activity in New Mexico is discussed in relation to the major physiographic provinces in the state and local geologic conditions within each province.

The existence of moderate seismicity in New Mexico was documented by a number of early investigators (Reid, 1911; Northrop, 1945, 1947; Richter, 1959). Early studies were based totally on reports of felt shocks, some fairly strong, dating from the latter half of the nineteenth century. Perhaps because of the relatively low population of New Mexico and an absence of strong shocks after the early part of this century, instrumental studies of seismic activity did not begin until 1960. A number of papers on instrumental studies have been published; those related most directly to the seismicity of the state are Sanford (1965), Sanford and Cash (1969), Toppozada and Sanford (1972), Sanford and others (1972), Northrop and Sanford (1972), Sanford and Toppozada (1974), Hoffman (1975), von Hake (1975), and Sanford and others (1979). Northrop (1976) published a paper on New Mexico's seismicity that emphasized a large amount of non-instrumental data he had accumulated on the state's earthquakes since the early 1930's.

ACKNOWLEDGMENTS—Much of the information presented in this paper could not have been developed without collaboration with other institutions. We are particularly indebted to D. H. Shurbet, Texas Tech University, and David Dumas, University of Texas (Austin), for readings from their seismic stations.

At New Mexico Institute of Mining and Technology, a number of graduate and undergraduate students have been involved in data acquisition and analyses of New Mexico earthquakes. Recent work by assistants Terry Wallace, Scott Sandford, Joel Sheldon, Tim Wallace, and Roger Ward was particularly helpful in preparing this report.

We would like to acknowledge the contributions and advice of Dan Cash, John Stewart, Norma McFarland, Joyce Wolff, and Deborah Wechsler at Los Alamos Scientific Laboratory in the compilation of LASL epicenters. Fred Homuth and Ted Handel were responsible for much of the design and installation of the LASL regional network.

The authors are pleased to acknowledge the contribution of Jerry Locke (U.S. Geological Survey-retired) to this study.

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1980

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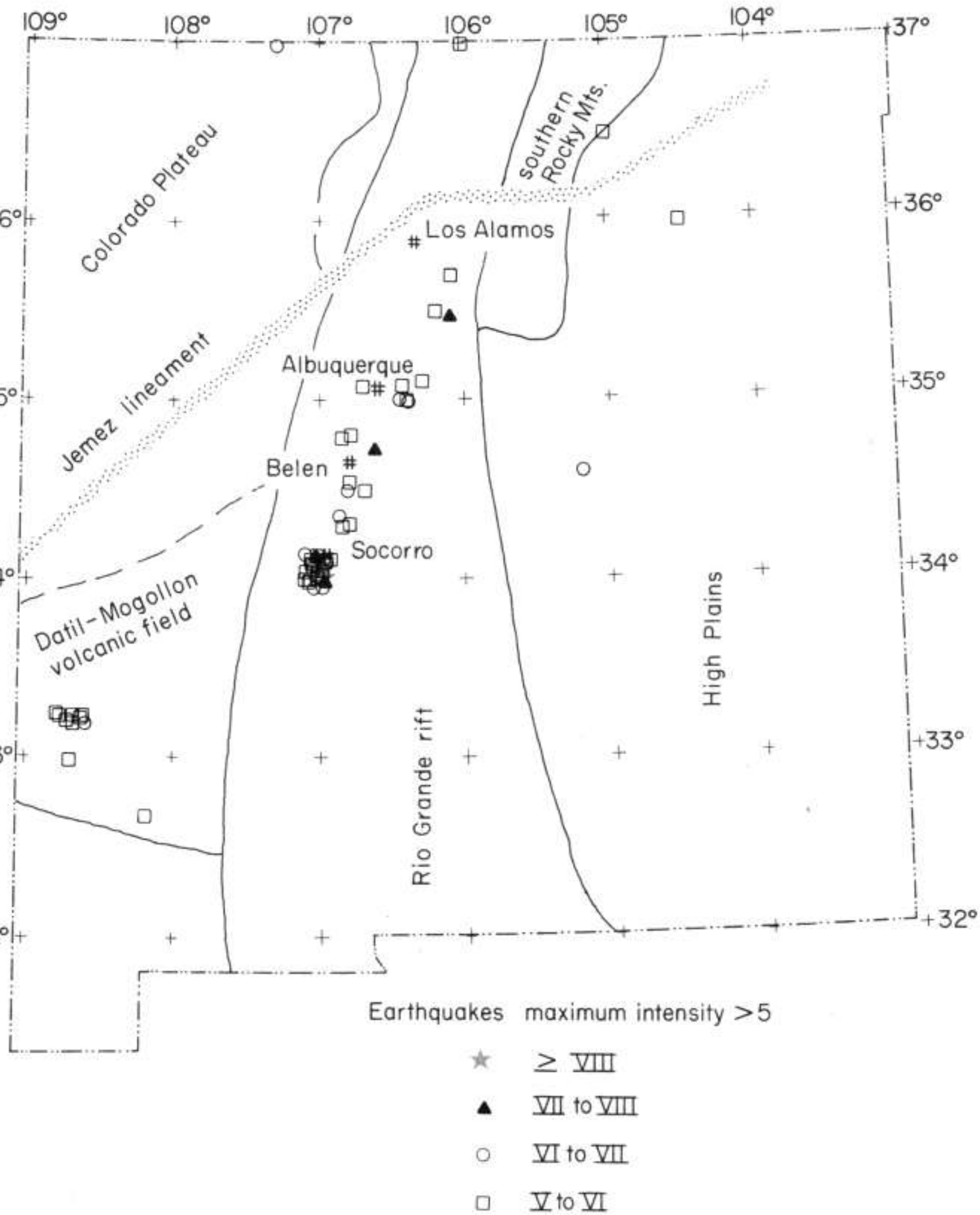

FIGURE 1—Locations of earthquakes reported prior to 1962 with maximum intensities of V or greater. Also shown on the map are the major physiographic provinces in New Mexico.

Abstract

The seismicity of New Mexico and its relation to major physiographic provinces and local geologic conditions within each province is presented. Earthquake data analyzed are 1) felt shocks before 1962 with maximum intensities of V or greater and 2) instrumentally located shocks with local magnitudes of 1.5 or greater for the period 1962-1977. Reports of felt shocks are almost exclusively from the Rio Grande rift, whereas the instrumental epicenters are distributed throughout the state. The instrumental data indicate a very low level of seismic activity in New Mexico relative to southern California. The data also reveal that earthquakes are most numerous in the Rio Grande rift although not as strong as those that occur in the High Plains and Colorado Plateau, two geologically stable provinces that border the rift. The more or less uniformly weak seismicity throughout the state suggests that earthquake activity is controlled more by local geologic conditions than by a general regional stress field. Some unusual local conditions that may be producing earthquakes are injection of magma into the crust in the Rio Grande rift near Socorro and hydrocarbon recovery practices in the High Plains of southeast New Mexico. Most activity in the High Plains and Colorado Plateau seems to be occurring along old buried faults that show no surface evidence of recent movement. The Jemez lineament, defined by a line of Pliocene and Pleistocene volcanoes through the southern part of the Colorado Plateau, across the Rio Grande rift, and into the northern High Plains, has seismic activity over much of its extent.

Earthquake activity prior to 1962

Information on locations and strengths of earthquakes prior to 1962 is based mostly on non-instrumentally determined values of earthquake intensity. Intensity values (indicated by Roman numerals) are assigned on the basis of reactions and observations of people during a shock and the degree of damage to structures (appendix I). Therefore, earthquake intensity depends primarily on distance from the epicenter and secondarily on ground conditions at the point of observation. Given many intensity observations, the point of maximum intensity and the area of perceptibility can be established. Both of these factors, particularly the area of perceptibility, can be roughly related to the earthquake magnitude (Richter, 1958; Slemmons and others, 1965; Wiegel, 1970; Toppozada, 1975). Earthquake magnitude is a measure of the strength of an earthquake, independent of distance, which is normally obtained from instrumental recordings.

A major weakness in determining the strengths and locations of earthquakes from intensity observations is that the method depends on population density. In sparsely settled areas like much of New Mexico, moderate shocks may go completely unreported or reported at low intensity values that do not indicate the true strengths of the earthquakes. Even in areas of relatively high population density, such as that along the Rio Grande valley, the point of maximum intensity or area of perceptibility may not be defined because of too few observations.

The reliability of the early reports of earthquakes must also be considered. Some of the intensities for strong earthquakes in New Mexico prior to 1900 are based on reports from local residents tens of years after the shocks (Bagg, 1904). Newspaper accounts of earthquakes have also been used to estimate earthquake intensity (Northrop, 1961, 1976). In most cases, this method has proved to be a fairly reliable procedure. However, in at least two instances the effects of earthquakes in the Rio Grande valley at Socorro were exaggerated in stories appearing in newspapers in Albuquerque and El Paso (Sanford, 1963; Ashcroft, 1974).

Despite their imperfect nature, non-instrumental data are valuable because they are available for a period of time roughly eight times longer than that for instrumental data. Moderate to strong earthquakes are rare events in New Mexico; hence, the longer the earthquake history available, the more reliable the estimates of seismicity in the state.

Earthquake data 1849-1961

Although settlement by the Spanish began in the early 17th century, little is known of seismic activity in New Mexico prior to its becoming part of the United States in 1848. No doubt reports of earthquakes exist in Spanish and Mexican archives, but such information is difficult to extract and to our knowledge such an attempt has not been made. The earliest report of earthquakes after U.S. occupation is the description of a swarm of shocks in the Rio Grande rift at Socorro by a U.S. Army surgeon (Hammond, 1966). The swarm, which contained 22 felt shocks, commenced on December 11, 1849, and lasted until February 8, 1850. No shock in this swarm was reported felt at distances greater than 25 km; maximum intensities, therefore, were probably less than or equal to IV. Similar sequences of shocks located away from population centers along the Rio Grande valley or elsewhere in the state could easily have gone unreported before the start of instrumental studies.

For the period 1849-1961, Northrop (1961, 1976) cites evidence, primarily from old newspaper files, for over 600 felt earthquakes in New Mexico. Approximately 95 percent of these shocks occurred along a 150-km section of the Rio Grande rift from Albuquerque to Socorro; the majority occurred in the 75 km from Belen to Socorro. The concentration of reported activity in the Belen-Socorro area cannot be attributed to population density because the population from Belen to Albuquerque has always exceeded the population from Belen to Socorro.

However, when considering the entire state, Northrop's data are influenced by the distribution of population. Population density has been higher in the Albuquerque-to-Socorro section of the Rio Grande valley than in most other sections of the state. To reduce bias arising from the distribution of population, only shocks with maximum reported intensities (modified Mercalli) of V or greater are listed in table 1 and plotted in fig. 1. The primary source of data for table 1 is Coffman and von Hake (1973). However, when reference to original material indicated these investigators made errors, changes were made. Two examples are an increase in the intensity of the November 15, 1906, shock and a change in the location of an earthquake near Cerrillos on May 28, 1918. The locations listed in table 1 were selected to avoid overlapping of symbols in fig. 1, particularly near Socorro. With few exceptions, shocks for this time period can be placed only at the nearest population center.

TABLE 1—EARTHQUAKES REPORTED FELT IN NEW MEXICO PRIOR TO 1962 with maximum intensities (modified Mercalli) of V or greater.

Date	Origin time GMT			Approximate location		Maximum intensity
mon/day/year	hr	min	secs	lat ° N.	long ° W.	(modified Mercalli)
Apr. 28, 1868				34.00	107.00	V
Apr. 1869				34.10	107.00	VII
1879				34.05	107.00	V
Jul. 6, 1886				34.00	107.05	V
Jul. 12, 1893	13	30		35.00	106.40	V
Sep. 7, 1893				34.70	106.60	VII
Oct. 7, 1895				34.50	106.70	V
Oct. 31, 1895	12			34.05	107.05	VI
1897				33.95	107.00	VI
Jan. 20, 1904	2	10		33.95	107.05	VI
Jan. 20, 1904	9			34.10	107.10	V
Jan. 30, 1904	12	30		34.10	107.05	V
Mar. 9, 1904	7	30		34.10	107.00	V
Sep. 6, 1904	11	30		34.10	106.95	V
Jul. 2, 1906	10	15		34.15	107.10	VI
Jul. 12, 1906	12	15		33.95	106.95	VII to VIII
Jul. 16, 1906	19			34.00	106.95	VIII
Nov. 15, 1906	12	15		34.05	106.95	VIII
Jul. 18, 1913				34.00	107.00	?
Dec. 6, 1913	0	15		34.10	106.80	?
May 28, 1918	11	30		35.45	106.10	VII
Feb. 1, 1919	20	30		34.00	107.10	V
Aug. 13, 1924	4	23		36.00	104.50	V
Dec. 3, 1930	21	36		35.00	106.40	V to VI
Feb. 3, 1931	23	45		35.10	106.45	V
Feb. 5, 1931	4	48		35.00	106.45	VI
Jan. 8, 1934	1	32		34.05	107.10	V
May 7, 1934	5	22		32.70	108.20	V
Feb. 21, 1935	1	25		34.50	106.80	VI
Feb. 21, 1935	3	5		34.55	106.80	V
Dec. 18, 1935	5	33		34.80	106.80	V to VI
Dec. 19, 1935	1	57		34.80	106.85	V to VI
Sep. 17, 1938	17	20		33.20	108.60	VI
Sep. 20, 1938	5	40		33.25	108.60	V
Sep. 29, 1938	23	34		33.25	108.65	V
Nov. 1, 1938	1	26		33.00	108.70	V to VI
Nov. 27, 1938	0	13		33.20	108.65	V
Dec. 28, 1938	22	7		33.20	108.70	V
Jun. 4, 1939	1	15		33.25	108.75	V
Aug. 4, 1941	7	40		34.15	107.05	V
Nov. 6, 1947	16	50		35.00	106.40	VI
May 23, 1949	7	22		34.60	105.20	VI
Aug. 3, 1952	20	42		36.50	105.00	V
Aug. 17, 1952	10	45		35.50	106.20	V
Oct. 7, 1952	9	20		37.00	106.00	V
Nov. 3, 1954	20	39		35.10	106.70	V
Aug. 3, 1955	6	39	42.0	37.00	107.30	VI
Aug. 12, 1955	16	20		35.70	106.10	V
Apr. 26, 1956	3	30		35.10	106.30	V
Jul. 22, 1960	15	49		34.30	106.85	V
Jul. 23, 1960	14	15		34.35	106.85	VI
Jul. 24, 1960	10	37		34.30	106.80	V
Jul. 3, 1961	7	6		34.10	106.95	VI

Rio Grande rift seismicity

Most of the earthquakes in fig. 1 and table 1 are along the Rio Grande valley, primarily between Albuquerque And Socorro. The concentration of seismic activity along this belt during the period 1849-1962 seems real. Some of the shocks in this region, particularly at Socorro, were of such strength (felt over areas up to 245,000 sq km) that they would have been detected anywhere in the state regardless of the distribution of population (Sanford and others, 1979).

A characteristic of the strong Socorro shocks as well as many other known earthquakes in the rift from Albuquerque to Socorro is that they are associated with earthquake swarms. As has been noted for many years, earthquake swarms are observed in the vicinity of active volcanoes and in regions that have had volcanic activity in geologically recent times (Richter, 1958). The possible significance of the earthquake swarms in the Rio Grande rift is that they may be related to injection of magma into the crust (Sanford and others, 1977; Sanford and others, 1979).

Listed in table 2 are parameters for known earthquake swarms in the Rio Grande rift during the period 1849-1961. By far the strongest and longest earthquake swarm was the 1906-07 swarm at Socorro, which appears comparable to the Matsushiro swarm that may have been caused by magmatic intrusion at shallow depth (Stuart and Johnston, 1975). Although the evidence is not absolutely conclusive, the distribution of isoseismals for the 1906-07 swarm (Reid, 1911) suggests hypocenters beneath the Socorro Mountain horst block, a relatively young north-south structural feature in the central part of the Rio Grande rift (Chapin and Seager, 1975). The December 1935 swarm centered near Belen also seems to have originated near the axis of the rift. At Los Lunas, 18 km north of Belen, the shocks of the 1935 swarm were much weaker than at Belen—an unlikely observation if the epicenters were on the rift margins, which are located approximately 30 km to the east and west of these two communities. Recent instrumental studies (Sanford and others, 1979) between Albuquerque and Socorro show considerable seismic activity within the rift but little associated with the well-defined boundary faults.

Late Pliocene and Quaternary basalt flows, from north of Albuquerque to south of Socorro, are generally confined to the central part of the rift (Kelley and Kudo, 1978; Bachman and Mehnert, 1978). This observation in conjunction with the location of earthquake swarms may indicate that magma is continuing to be injected into the central part of the rift.

TABLE 2—CHARACTERISTICS OF EARTHQUAKE SWARMS in the Rio Grande rift, 1849–1961.

Date	Duration in weeks	Location of nearest population center	Number of reported shocks	Maximum intensity (m.M.) of strongest earthquake(s)	Reference	Remarks
Dec. 11, 1849 to Feb. 8, 1850	8	Socorro	22	IV	Hammond (1966)	Extent of felt region suggests a location beneath Socorro Mountain, an intra-graben horst block
Sept. 1893	12	Los Lunas	Daily?	VII	Woollard (1968), Coffman and von Hake (1973), Northrop (1976)	One listing (Woollard, 1968) indicates daily shocks at Sabinal (35 km south of Los Lunas) with maximum intensities >V for 3 months
Jan. 19, 1904 to March 8, 1904	8	Socorro	34	V	Bagg (1904), Woollard (1968)	Newspaper accounts indicate that shocks on September 10, 1904, at Socorro were not a continuation of this swarm
July 2, 1906 to Jan. 1907	28	Socorro	Daily	VIII(2)	Reid (1911)	Distribution of isoseismals suggests hypocenters beneath Socorro Mountain, an intra-graben horst block
Dec. 12, 1935 to Dec. 30, 1935	3	Belen	>24	V-VI	Neumann (1937), Coffman and von Hake (1973)	At Los Lunas (18 km north of Belen) shocks were much weaker than at Belen. This suggests epicenters near the central part of the rift rather than the margins

Earthquake activity after 1961

Prior to 1962, the number of seismographs in New Mexico and bordering states was inadequate to locate any but a few moderately strong earthquakes in the region. This situation changed in late 1961 and early 1962 when stations at Albuquerque (ALQ) and Las Cruces (LCN), New Mexico, and Payson (TFO), Arizona, went into continuous operation. Readings from these stations as well as earlier stations at Tucson (TUC), Arizona, Lubbock (LUB), Texas, and Socorro (SNM), New Mexico, permitted locations of a relatively large number of earthquakes throughout the region.

For the period 1962-1972, 211 earthquakes in New Mexico and bordering areas were located by New Mexico Institute of Mining and Technology (NMT) (Sanford and others, 1976). Approximately 30 percent of these shocks were also located by the National Earthquake Information Service (U.S. Geological Survey) and the governmental agencies preceding it (U.S. Coast and Geodetic Survey and National Oceanic and Atmospheric Administration).

In September 1973 the number of located shocks in the northern half of New Mexico and southern margin of Colorado jumped sharply when Los Alamos Scientific Laboratory (LASL) installed an array of continuously recording stations. Another sharp increase in the number of shocks located in central New Mexico occurred in 1976 when the USGS-Albuquerque Seismological Laboratory (ASL) installed a permanent array of stations in and around the Albuquerque-Belen Basin. Since 1973, NMT has continued to locate earthquakes, but most of these lie in the southern half of New Mexico, west Texas, and northern Mexico.

Earthquake data 1962-1977

Listed in table 3 are the dates, origin times, locations, and magnitudes of earthquakes in New Mexico for the 16-yr period from 1962 through 1977. Also listed are the organizations that determined all earthquake parameters except magnitude: New Mexico Institute of Mining and Technology (NMT), U.S. Geological Survey (USGS), Los Alamos Scientific Laboratory (LASL), and USGS-Albuquerque Seismological Laboratory (ASL). Assignment of magnitude was made by NMT following a procedure described later.

USGS data were compiled from listings by the National Earthquake Information Service. LASL epicenters were from a publication by Wechsler and others (1980). Information on earthquakes from ASL was obtained from reports by Jaksha and others (1978) and Jaksha and Locke (1978).

Table 3 lists only earthquakes whose M_L (local magnitudes) were 1.5 or greater. The limitation on minimum magnitude was made to keep the numbers of listed shocks within reasonable bounds. Hundreds of earthquakes with magnitudes less than 1.5 have been located in and bordering the Rio Grande rift by local arrays of seismograph stations operated by NMT, LASL,

TABLE 3—INSTRUMENTAL ORIGIN TIMES, EPICENTERS, AND MAGNITUDES for New Mexico earthquakes from 1962 through 1977. Reporting organizations —NMT (New Mexico Institute of Mining and Technology), USGS (U.S. Geological Survey), LASL (Los Alamos Scientific Laboratory), and ASL (USGSAlbuquerque Seismological Laboratory).

Date yr/mo/day	Origin time GMT	Location lat ° N.	Location long ° W.	Located by NMT	Located by USGS	Located by LASL	Located by ASL	No. of stations	Magnitude (M_L)
62 1 3	23:29:52.6	35.32	103.64	X				5	2.60
62 1 24	15:12:43.8	33.96	106.86	X				3	1.84
62 1 24	15:53:14.6	33.96	106.86	X				3	1.50
62 3 22	04:23:53.4	34.25	106.51	X				3	1.74
62 4 9	23:42:58.0	34.21	106.44	X				3	1.76
62 5 2	23:21:17.7	34.22	107.05	X				3	1.56
62 6 14	07:27:55.8	35.68	106.74	X				6	1.87
62 6 25	02:35:27.3	34.20	108.10	X				3	1.56
62 6 27	04:49:16.0	33.95	107.01	X				3	1.63
62 9 1	16:15:07.9	34.16	106.66	X				5	2.97
62 12 15	20:20:34.3	33.97	106.86	X				4	1.87
63 2 22	07:02:08.1	32.42	106.99	X				6	2.47
63 2 22	08:53:18.1	32.45	106.94	X				5	1.51
63 3 6	14:49:36.3	33.63	107.68	X				4	1.68
63 3 8	06:16:40.0	32.95	107.08	X				4	1.56
63 5 27	12:54:56.5	32.72	107.82	X				4	1.61
63 6 2	05:07:34.6	34.23	106.46	X				9	1.96
63 6 6	08:05:33.3	36.60	104.40	X				9	2.74
63 7 3	19:08:00.5	33.91	106.90	X				6	1.92
63 8 19	00:08:23.4	32.44	107.15	X				5	2.11
63 11 25	12:52:33.8	36.54	105.37	X				9	2.41
63 12 19	16:47:28.4	35.14	104.13	X				9	2.88
63 12 30	08:48:14.6	34.03	106.54	X				3	1.66
64 2 11	09:24:31.0	34.35	103.73	X				4	2.49
64 3 3	01:26:26.6	34.97	103.59	X				5	2.22
64 6 19	05:28:38.8	33.09	105.95	X				5	1.71
65 2 3	11:32:34.4	35.10	103.80	X				9	2.92
65 3 9	19:04:48.5	33.87	106.90	X				6	2.54
65 4 10	07:00:55.0	33.94	107.05	X				7	2.00
65 5 27	12:17:44.1	33.90	107.01	X				4	1.82
65 5 27	18:50:53.9	33.88	106.73	X				4	2.01
65 5 27	18:58:40.9	33.90	106.71	X				4	2.03
65 5 29	13:01:08.2	33.87	106.69	X				5	2.03
65 6 4	01:58:58.7	33.90	106.81	X				5	1.73
65 7 28	03:52:07.4	33.96	106.82	X				7	2.26
65 7 28	04:38:53.4	33.80	106.70	X				4	2.59
65 12 22	03:33:29.6	34.02	106.78	X				4	2.15
65 12 22	04:04:51.9	34.02	106.78	X				3	1.91
65 12 29	00:05:24.1	35.03	105.78	X				4	2.65
66 1 23	01:56:39.8	36.96	106.95	X				9	4.29
66 3 24	20:10:59.3	36.80	108.30		X			6	?
66 4 21	14:14:18.7	35.29	103.32	X				8	2.28
66 9 9	17:43:58.4	36.70	108.30		X			5	?
66 9 17	21:30:13.0	34.94	103.71	X				7	2.23
66 9 24	07:33:46.4	36.43	105.08	X				9	2.71
66 9 24	08:27:06.6	36.44	105.09	X				9	2.44
66 9 25	10:10:41.0	36.34	105.08	X				8	2.75
66 9 25	12:22:40.5	36.45	105.14	X				8	2.76
66 10 6	06:29:56.0	35.21	104.27	X				8	2.30
66 10 6	10:19:08.2	34.04	106.85	X				4	2.35
67 1 16	18:14:37.2	34.43	106.85	X				5	1.64
67 7 29	05:49:39.5	33.25	108.47	X				6	2.10
67 9 29	03:52:48.0	32.27	106.91	X				8	2.04
68 3 9	21:54:25.7	32.70	106.05	X				9	2.91
68 3 23	11:53:38.7	32.70	106.05	X				6	2.24
68 5 2	02:56:43.8	33.02	105.27	X				5	2.58
68 5 15	10:13:04.8	34.27	106.84	X				8	2.32
68 5 19	11:02:56.6	34.50	107.98	X				8	2.26
68 5 29	02:09:02.2	34.39	107.75	X				3	2.47
68 7 25	04:54:34.3	33.99	106.85	X				3	1.84
68 8 21	23:47:33.0	35.10	107.52	X				4	1.69
68 8 22	02:22:25.5	34.33	105.80	X				4	2.06
69 1 30	05:17:38.4	34.22	106.75	X				9	3.42
69 3 4	21:09:13.9	34.72	105.85	X				3	2.30
69 5 28	05:06:22.5	35.45	107.35	X				6	2.43
69 6 1	17:18:24.2	34.23	105.18	X				6	1.97
69 6 8	11:36:01.9	34.23	105.18	X				8	2.39
69 6 28	14:49:11.6	35.26	107.56	X				4	1.55
69 7 4	14:43:33.0	36.15	106.13	X				9	2.85
69 7 30	02:05:13.0	34.39	106.99	X				3	1.73
69 8 23	21:41:54.2	34.70	108.44	X				9	2.66
69 9 13	23:05:31.5	36.86	105.88	X				6	2.27
70 1 12	11:21:15.1	35.89	103.40	X				7	3.26
70 5 22	09:43:35.6	35.64	106.00	X				4	1.53
70 7 3	11:41:25.0	34.90	105.91	X				3	1.60
70 7 31	11:57:31.2	35.28	106.19	X				8	2.06
70 8 7	11:59:06.0	35.40	105.89	X				8	1.97
70 11 28	07:40:11.8	35.10	106.61	X				9	3.18
70 11 30	05:35:20.5	36.25	105.49	X				8	2.49
71 1 4	07:39:07.0	35.10	106.60	X				9	3.55
71 1 6	10:56:31.5	34.15	106.79	X				9	2.75
71 1 27	07:56:28.3	34.06	106.60	X				8	2.60
71 2 13	09:22:55.0	33.18	108.07	X				4	1.79
71 2 18	11:28:14.3	36.30	105.78	X				9	2.76
71 3 25	02:43:02.4	34.58	106.03	X				3	1.73
71 4 28	11:36:52.1	36.13	105.96	X				9	2.74
71 5 22	22:31:18.6	35.43	107.76	X				5	2.31
71 6 4	03:55:14.7	36.19	106.32	X				8	2.34
71 6 24	22:12:36.7	36.70	105.67	X				4	1.88
71 12 6	05:18:13.0	36.15	106.11	X				9	2.90
71 12 6	05:22:50.0	36.10	106.17	X				6	2.14
71 12 6	05:38:08.2	36.09	106.19	X				6	2.03
71 12 6	06:14:09.6	36.08	106.14	X				7	2.31
71 12 11	02:28:21.4	35.72	105.29	X				3	1.92
71 12 23	14:24:37.0	34.42	107.02	X				4	2.04
71 12 27	11:08:50.9	35.79	106.96	X				3	1.68
72 2 20	23:09:49.5	36.36	104.87	X				3	1.50
72 2 20	23:22:54.4	36.35	104.94	X				4	2.21
72 2 27	09:11:48.9	34.15	106.81	X				4	1.64
72 2 27	15:50:03.9	32.89	106.04	X				5	2.24
72 3 28	01:53:33.7	36.17	106.06	X				9	2.67
72 3 28	02:03:16.6	36.14	106.15	X				8	2.26
72 3 31	20:14:19.8	36.11	106.04	X				5	2.37
72 4 15	00:13:28.0	36.58	108.53	X				5	1.74
72 5 6	07:35:05.5	35.40	107.46	X				6	2.16
72 5 16	22:13:44.8	34.20	106.88	X				4	1.68
72 5 20	19:15:45.7	35.40	107.36	X				6	2.70
72 7 26	04:35:43.9	32.68	103.98	X				6	2.90
72 10 11	18:18:29.4	32.74	107.92	X				5	2.34
72 11 24	01:13:33.2	32.03	108.34	X				6	2.72
72 12 18	04:07:36.2	35.42	107.16	X				7	2.68
73 1 9	05:08:44.0	32.00	107.40	X				3	1.64
73 2 3	01:21:38.6	36.85	108.25	X				4	2.13
73 2 3	21:54:08.8	36.25	108.17	X				3	1.53

Date yr/mo/day	Origin time GMT	Location lat° N.	Location long° W.	Located by NMT	Located by USGS	Located by LASL	Located by ASL	No. of stations	Magnitude (M_L)
73 2 26	10:51:22.7	35.45	103.50	X				4	1.96
73 3 17	07:43:06.0	36.14	106.19	X				8	2.45
73 3 22	02:45:50.0	31.35	108.50	X				4	2.86
73 7 22	15:22:12.7	33.00	108.10	X				3	2.33
73 7 27	02:46:44.7	36.50	108.60	X				3	2.31
73 8 6	12:47:11.5	32.40	107.30	X				3	1.66
73 9 10	20:29:23.7	34.42	106.85	X				7	2.40
73 9 22	23:38:37.1	34.46	106.95	X				8	2.50
73 10 16	02:10:59.5	35.60	108.25	X				3	1.83
73 11 14	07:56:08.0	36.95	107.00			X		?	2.10
73 12 24	02:20:14.9	35.26	107.74		X			16	3.44
73 12 24	15:06:12.5	35.52	106.10			X		?	1.80
74 1 12	14:14:00.5	35.20	107.60	X				7	1.85
74 1 17	23:04:20.8	36.15	106.20			X		?	1.80
74 3 13	16:15:29.0	34.50	106.90	X				3	2.20
74 3 23	10:44:15.0	36.50	107.08			X		?	1.90
74 3 28	22:14:38.4	35.22	107.55			X		?	1.60
74 3 28	22:24:40.4	35.22	107.55			X		?	1.50
74 4 8	16:13:55.3	34.20	106.80	X				3	1.60
74 4 12	18:14:40.7	34.50	107.00	X				3	2.30
74 5 4	20:38:45.5	35.55	108.98			X		?	1.70
74 6 22	09:53:42.8	35.08	106.70			X		?	1.90
74 7 11	11:26:57.0	35.32	107.78			X		?	2.00
74 7 31	17:34:48.5	33.10	104.20	X				4	2.30
74 8 26	07:33:22.0	34.40	105.80	X				8	2.30
74 8 30	22:57:35.2	34.87	107.06	X				8	2.40
74 9 26	23:44:08.5	32.80	106.20	X				5	3.00
74 9 29	13:13:44.2	32.80	108.65	X				9	3.20
74 9 29	14:26:03.0	32.80	108.65	X				3	2.20
74 10 11	11:07:25.8	32.80	108.70	X				7	2.30
74 10 15	09:36:06.7	33.83	106.58			X		?	1.80
74 10 15	10:05:02.4	33.83	106.58			X		?	1.80
74 10 15	10:07:57.9	33.85	106.55	X				6	2.00
74 10 15	12:47:38.8	35.25	107.08			X		?	2.10
74 10 18	04:30:57.3	35.08	106.82			X		?	1.80
74 11 1	10:45:49.6	33.80	106.60	X				6	2.00
74 11 21	16:22:58.6	32.50	106.30	X				4	2.70
74 11 22	14:11:13.2	33.00	105.10	X				5	1.60
74 11 28	03:35:20.5	32.63	104.01	X				6	3.80
74 12 28	23:24:11.5	35.37	107.37			X		?	2.10
75 2 2	20:39:22.6	35.10	103.10	X				8	2.90
75 2 9	09:12:35.7	36.18	106.23			X		?	1.50
75 3 5	03:48:05.3	34.55	107.12	X				7	2.20
75 3 6	07:56:55.9	34.55	107.14	X				6	2.20
75 3 7	03:16:13.0	34.55	107.16	X				10	2.80
75 3 7	17:36:08.7	34.55	107.16	X				10	2.90
75 3 7	18:33:33.9	34.50	106.90			X		?	1.50
75 5 16	01:38:18.9	36.92	104.95			X		?	1.50
75 5 16	07:26:22.5	36.48	104.70			X		?	1.90
75 5 21	04:46:59.0	36.97	107.22			X		?	1.50
75 6 21	05:41:35.2	36.08	104.03			X		?	2.00
75 6 26	07:03:43.4	36.95	105.45			X		?	2.90
75 6 27	01:39:24.7	34.19	106.93	X				6	1.60
75 6 28	07:20:23.2	34.20	106.90	X				10	1.90
75 7 20	07:44:37.8	34.57	106.73			X		?	1.60
75 9 6	03:46:50.4	36.18	106.23			X		?	1.80
75 9 10	01:01:48.2	36.73	105.67			X		?	1.50
75 9 29	11:09:42.4	36.00	106.87			X		?	2.70
75 9 29	13:17:19.2	36.00	106.87			X		?	1.50
75 10 10	11:16:55.9	33.30	105.00	X				3	2.00
75 10 17	15:45:02.5	35.38	108.20			X		?	1.90
75 12 3	10:12:22.8	32.83	108.66		X			14	3.40
76 1 5	06:23:32.9	35.84	108.34		X			95	4.10
76 1 14	07:01:31.5	34.10	106.80	X				8	2.20
76 1 16	22:07:17.3	35.57	107.87			X		?	1.80
76 1 25	04:48:27.5	32.00	103.10	X				12	3.20
76 3 7	12:18:25.4	35.68	107.98			X		?	1.70
76 3 20	16:15:58.0	32.20	103.10	X				5	1.70
76 3 27	22:25:22.0	32.20	103.10	X				8	2.00
76 4 1	14:40:27.8	33.80	105.90	X				3	1.60
76 4 1	14:46:58.0	33.90	106.00	X				9	2.10
76 4 1	14:51:17.0	33.90	105.90	X				3	1.50
76 4 6	18:09:00.2	33.90	106.00	X				10	2.70
76 4 18	03:48:18.5	33.90	106.00	X				6	1.60
76 4 30	19:20:35.7	32.00	103.30	X				4	1.50
76 4 30	19:51:12.8	32.00	103.20	X				3	1.60
76 5 1	11:13:40.7	32.40	103.10	X				8	2.70
76 5 2	00:32:36.6	36.28	106.73			X		?	2.20
76 5 3	06:52:59.0	32.40	105.60	X				4	2.40
76 5 3	08:00:39.9	32.00	103.20	X				4	1.50
76 5 3	11:27:40.3	32.00	103.10	X				4	1.50
76 5 6	17:18:23.8	32.00	103.20	X				6	1.80
76 5 9	03:54:09.0	34.25	106.86				X	?	1.70
76 5 21	13:17:35.0	32.30	105.30	X				3	2.30
76 6 1	16:40:00.8	36.30	106.20			X		?	1.90
76 6 9	17:37:45.0	34.46	106.99				X	?	1.70
76 6 24	15:27:32.0	35.62	103.28		X			19	3.00
76 6 26	12:55:39.3	36.13	106.27			X		?	1.50
76 7 5	12:39:19.4	36.13	106.25			X		?	1.80
76 7 6	12:48:45.2	36.08	106.27			X		?	1.50
76 8 30	13:07:32.3	33.30	105.70	X				3	1.50
76 9 17	02:47:46.9	32.20	103.10	X				8	2.10
76 12 23	08:36:58.0	34.68	105.77				X	?	1.90
76 12 31	07:53:46.5	36.72	106.65			X		?	1.80
76 12 31	07:53:58.7	36.57	106.67			X		?	1.80
77 1 4	18:31:37.6	32.36	106.92		X			10	2.70
77 1 4	23:41:58.0	34.03	106.00				X	?	2.40
77 1 5	12:19:02.0	34.05	106.00				X	?	1.70
77 2 18	14:10:36.8	32.20	103.10	X				4	1.50
77 3 5	03:00:54.7	35.92	108.29		X			47	3.70
77 3 9	18:35:33.0	35.80	108.17			X		?	1.70
77 3 16	10:00:41.3	36.97	106.98			X		?	1.70
77 3 20	07:54:09.0	32.20	103.10	X				7	2.10
77 4 3	19:26:49.4	36.10	106.25			X		?	1.90
77 4 7	05:45:40.5	32.20	103.10	X				8	2.30
77 4 22	22:56:37.0	32.20	103.10	X				3	1.70
77 4 26	09:03:07.5	32.00	103.10	X				11	2.50
77 6 2	06:48:16.3	34.02	107.06	X				7	1.50
77 8 19	09:22:06.0	34.01	107.06	X				5	1.90
77 8 22	15:10:56.2	35.62	107.23			X		?	1.50

and ASL. Results of these microearthquake surveys are summarized in Sanford and others (1979).

Another reason for limiting the listing in table 3 to shocks with $M_{L}.^{3}1.5$ is to reduce the effects of station distribution on the statewide data set. Because the majority of New Mexico seismograph stations from 1962 through 1977 were in or near the Rio Grande valley, the probability of locating shocks in the central part of the state was higher than elsewhere. A study by Sanford and others (1976) indicates that the minimum-magnitude shock locatable at the outer boundaries of the state throughout the study period, 1962-1977, was about 2.2. Therefore, a great deal of station bias remains in the shocks listed in table 3, particularly in the years 1973-1977 when LASL, ASL, and NMT arrays were in operation.

The strongest earthquake during the 16-yr period occurred at Dulce on the New Mexico-Colorado border on January 23, 1966. This earthquake was followed by a large number of aftershocks (Cash, 1971; Hoffman and Northrop, 1978), many of which were located by the USGS and NMT. These aftershocks are not listed in table 3.

Location procedures and accuracy

NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY - The procedure used by NMT to determine epicenters is a computer adaptation of the graphical arc method using Pn and Pg arrival times. (Pn-compressional phase critically refracted at Mohorovfčić discontinuity [Moho] and traveling as head wave at base of crust; Pg-compressional wave traveling directly through crust from source to seismograph.) The crustal structure adopted for the location program consists of an upper crust 22.3 km thick with a velocity of 6.15 km/sec and a lower crust of the same thickness with a velocity of 6.60 km/sec. The upper mantle velocity immediately below the Moho in the crustal model is 8.10 km/sec.

The change in crustal structure over the state is substantial. Crustal thicknesses range from 30 to 51 km, upper crustal velocities from 5.8 to 6.2 km/sec, and sub-Moho velocities from 7.6 to 8.25 km/sec (Toppozada, 1974; Olsen and others, 1979). Because the same crustal structure is assumed throughout New Mexico in the NMT location program, systematic errors in the absolute location of epicenters are probable (Sanford and others, 1977). If reading errors are also considered, the mislocation of an event can be substantial. However, probably about 95 percent of the locations listed in table 3 are within 20 km of the true locations.

A comparison of earthquake parameters for 21 shocks located by both NMT and USGS revealed some rather large differences. The standard deviations of differences in origin time, latitude, and longitude were 2.5 seconds, 0.18 °, and 0.27 °, respectively. Instrumental locations obtained by both organizations for shocks that were felt over small areas (November 28, 1970; January 4, 1971; and November 28, 1974) seem to indicate that many NMT locations are more accurate than the USGS locations, probably because NMT hypo-centers are generally based on more near-station data than those obtained by the USGS.

A discussion of location errors is important because many geologists and geophysicists are tempted to associate earthquake epicenters with specific faults. The location errors cited above indicate that this procedure would be erroneous. Another reason for being careful about assigning earthquakes to specific faults is the area of fault surface associated with the majority of earthquakes listed in table 3. Ninety-eight percent of the shocks have local magnitudes of less than 3.5. An earthquake of magnitude 3.5 can be generated by displacement on fault surfaces ranging in area from 0.05 to 3.0 sq km (Thatcher and Hanks, 1973). Thus, many of the New Mexico earthquakes could have occurred on minor and unknown faults.

LOS ALAMOS SCIENTIFIC LABORATORY -At LASL, two basic computer programs are used for earthquake location: 1) a computer adaptation of the graphical arc technique and 2) a modified version of HYPO 71 (Lee and Lahr, 1975; Newton and others, 1976). The crustal model used by LASL in their location programs consists of a single-layer crust 40 km thick with a velocity of 6.0 km/sec overlying mantle rock with a velocity of 8.0 km/sec. Accuracy of the epicenters is ± 3 km for events interior to the LASL network and recorded by four or more stations. The accuracy is ± 10 km for events on the perimeter of the network, and no better than ±20 km for shocks outside the network (Sanford and others, 1979).

ALBUQUERQUE SEISMOLOGICAL LABORATORY -At ASL, the earthquake epicenters are obtained from the computer program HYPO 71 (Lee and Lahr, 1975). The crustal models used for ASL epicenters are: 1) a single-layer crust 39 km thick with a velocity of 6.0 km/sec overlying mantle rock with a velocity of 8.0 km/sec and 2) a two-layer crust, consisting of an upper crust 18.6 km thick with a velocity of 5.8 km/sec and a lower crust 21.3 km thick with a velocity of 6.5 km/sec overlying mantle rock with a velocity of 7.9 km/sec (Jaksha and Locke, 1978). Initially the first model was used for shocks outside the Rio Grande rift and the second model for those within the rift. However, comparisons of solutions using both crustal models indicate differences in space coordinates that are smaller than error estimates for the array. Since 1976, all epicenters have been obtained with the second crustal model regardless of the location of the earthquake (Jaksha and Locke, 1978). Accuracy of the location of epicenters is believed to be ± 2 km for events interior to the ASL network and ± 10 km for shocks located outside the array. ASL does not estimate locations for earthquakes occurring at distances greater than approximately 110 km from the center of their array.

Depths of focus

The depths of focus are poorly known for nearly all shocks listed in table 3 because the epicenters were not close (1-2 focal depths) to a recording station. Some of the events in table 3 that occurred within the LASL and ASL arrays may have accurately determined depths of focus. Original listings of hypocenters by LASL (Wechsler and others, 1980) and ASL (Jaksha and others, 1978; Jaksha and Locke, 1978) should be consulted for this information.

In the Socorro area of the Rio Grande rift, detailed studies of microearthquakes (nearly all with $M_L<1.5$) indicate no seismic activity below a depth of 13 km (Sanford and others, 1979). Similar studies of very small earthquakes by ASL and LASL in the Rio Grande rift north of Socorro indicate that most activity is occurring in the upper crust at depths of less than 20 km. Detailed microearthquake surveys have not been made in other physiographic provinces within the state.

Magnitudes

The magnitudes listed in table 3 are local magnitúdes (M_L) calculated by NMT. Because the very low magnification Standard Wood-Anderson instruments located at NMT and ASL seldom recorded regional earthquakes, calculation of the equivalent Wood-Anderson amplitudes from records produced by higher magnification instruments—such as those employed by WWSSN (the World Wide Standard Seismograph Network)—was necessary. The parameters required for the calculation are the amplitude and dominant period of the largest oscillations on the seismogram (nearly always the S phase for earthquakes in New Mexico) and the frequency response and magnification of the WWSSN instrument. From this information, maximum ground motion is calculated and then converted to an equivalent Wood-Anderson trace amplitude using a magnification of 2,800.

Magnitudes calculated by NMT were based on seismograms from stations located at Socorro, New Mexico (SNM), Tucson, Arizona (TUC), Lubbock, Texas (LUB), Golden, Colorado (GOL), and Albuquerque, New Mexico (ALQ). Because ALQ was central to the area under investigation, located at a quiet site, and operated both Wood-Anderson and WWSSN instruments, it was chosen as the standard for all NMT magnitude calculations. To minimize differences between ALQ and other station magnitudes, corrections were estimated from 211 regional earthquakes recorded between 1962 and 1972. The station corrections ranged from -0.13 at SNM to -0.50 at LUB relative to the ALQ magnitude. The earthquake strength determined by NMT was generally the average of magnitudes calculated from records from more than one station.

The same data set was used to calculate a correction for the standard $\log_{10}A_0$ versus distance table used to determine local magnitude. As noted by Richter (1958), the standard table was designed for earthquakes in southern California; therefore, it may not necessarily apply elsewhere. Without correction, local magnitudes of New Mexico earthquakes were found to be systematically shifted to larger values with increasing distance from the epicenters. Application of a correction of -0.0014 times the epicentral distance in kilometers was found to remove any dependence of magnitude on distance. The physical meaning of the correction is that seismic waves are less attenuated with distance in New Mexico than in southern California.

A comparison of 13 NMT and LASL magnitudes indicated the latter magnitudes were, on the average, approximately half a unit higher. A similar comparison between 21 LASL and ASL magnitudes indicated no significant difference on the average. Therefore, to make the listing of New Mexico shocks after September 1973 roughly consistent with the previous period of 11 2/3 yrs, two procedures were adopted—either 0.5 was subtracted from LASL or ASL magnitudes or a new magnitude was calculated by NMT.

The choice of ALQ station WWSSN seismograms as a standard for NMT magnitude calculations could explain the difference between NMT and LASL determinations. ALQ is known to record smaller ground vibrations than other stations at the same distance from a seismic disturbance (Jordan and others, 1965). This factor, in conjunction with the distance correction used by NMT, might account for the difference observed between NMT and LASL magnitudes. The procedure used by LASL to estimate magnitudes is based on a signal duration or coda length technique and is described by Newton and others (1976). ASL uses basically the same procedure as LASL (Jaksha and Locke, 1978).

Time variations in seismic activity

Time variations in seismic activity were examined in two ways: 1) the cumulative number of recorded earthquakes as a function of time and 2) the distribution of the number of earthquakes relative to magnitude as a function of time. To be meaningful, both analyses were applied only to shocks whose magnitudes exceeded or equalled 2.2. The latter is the established threshold magnitude; that is, the minimum strength earthquake above which the event count is substantially complete throughout New Mexico for the entire 16-yr study period.

Fig. 2 is a graph of the cumulative number of shocks 2.2) as a function of time. This figure shows that the rate of earthquake activity, as measured by number of recorded shocks, increased abruptly about 1970. This observation alone does not imply an increase in earthquake activity at all magnitude levels inasmuch as the number of weak earthquakes relative to the strong ones could have increased during the study period.

The distribution of numbers of earthquakes relative to magnitude can be quantified by using the linear relation

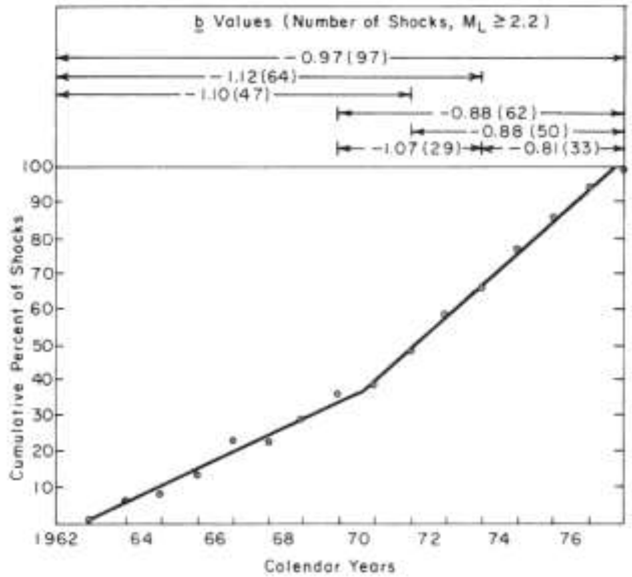

FIGURE 2—CUMULATIVE PERCENT OF SHOCKS (with $M_L \geq 2.2$) versus time in calendar years. Also shown are *b* values for different intervals of time from 1962 through 1977.

$$\log_{10}\Sigma N = a - bM_L \quad (1)$$

where $\log_{10}\Sigma N$ = logarithm of the cumulative number of detected shocks exceeding M_L, M_L = local magnitude,

and *a*, *b* = constants that depend on the observed seismicity.

Richter (1958) and others have established the validity of this linear relationship for many seismic areas in the world. The only constraint is that the linear fit be based on the observed earthquake data that fall above an established threshold magnitude. The relation probably becomes nonlinear at magnitudes approaching the strongest earthquake that a given region can sustain. However, the instrumental data on New Mexico earthquakes cover such a short period that no events at all near the largest possible earthquakes for this area are included in the data set.

Plotted on fig. 2 are the *b* values established from equation (1) for the seismic data collected over different time intervals. The calculated *b* values show a systematic shift from higher to lower values during the 1962-1977 period. This shift in values implies a progressive increase in the number of strong shocks relative to the weak shocks. Because the number of shocks above the threshold value also increased with time, the absolute level of seismicity at all observed magnitude levels increased with time—at a somewhat greater rate for the stronger shocks.

The time variation of seismicity along the Rio Grande rift, a Tertiary-Quaternary tectonic province occupying approximately 30 percent of the state, differs from that of the state as a whole. Of the 97 shocks in the 16-yr study that exceeded or equaled magnitude 2.2, 50 occurred in the Rio Grande rift; 25 during the 9-yr period from 1962

Estimates of seismicity

On the basis of data gathered from 1962 through 1977, the relation between cumulative number of earthquakes (EN) and magnitude for New Mexico earthquakes is

log$_{10}$åN =4.15 (± 0.06 s.d.) - 0.97 (± 0.02 s.d.) K. (2)

As indicated by the small values of the standard deviations (s.d.), the linear fit, which is based on 97 shocks with M_L Z2.2, is extremely good. Even for the high magnitudes, equation (2) matches observations closely; for example, the largest quake for the 16-yr period according to equation (2) should have had an M_L equal to 4.28, whereas the strongest observed quake had a calculated magnitude of 4.29 (January 23, 1966; 20:10:59).

An estimate of the seismicity of New Mexico for longer periods can be obtained by extrapolating equation (2). The results of this procedure are subject to great uncertainties primarily because significant temporal variations in observed seismicity, such as those discussed in the previous section, prohibit reliable estimates of *a* and *b* in equation (1). The observed temporal variations in the *b* value for New Mexico earthquakes (fig. 2) suggest that this value may be unstable. Small errors in this parameter can lead to large errors in estimated seismicity; for example, a ± 10 percent error in *b* can produce an uncertainty of one magnitude unit in the estimate of the strongest earthquake in New Mexico in a 100-yr period. Despite the uncertainties, extrapolation of relation (2) appears to be the best and perhaps only procedure for estimating the expected seismicity in New Mexico during the next century.

The relation in equation (2) can be extrapolated to 50- and 100-yr periods by adding to the first term on the right a quantity equal to the logarithm to the base 10 of 50/16 and 100/16. The resulting equations are

$$\log_{10}\Sigma N = 4.64 - 0.97\, M_L \text{ (50 yrs)}, \quad (3)$$

and

$$\log_{10}\Sigma N = 4.95 - 0.97\, M_L \text{ (100 yrs)}. \quad (4)$$

On the basis of these extrapolations, the strongest earthquakes that can be expected within New Mexico will be 4.8 in a 50-yr period and 5.1 in a 100-yr period.

The strongest earthquake in New Mexico during the past 100 yrs occurred near Socorro on November 15, 1906, and was felt over an area of 245,000 sq km. Several investigators have developed empirical relations between the area of perceptibility and magnitude for different physiographic provinces (Slemmons and others, 1965; Wiegel, 1970; Toppozada, 1975). The relations for the Rocky Mountain or Basin and Range provinces appear to be most applicable for the Socorro earthquake and they yield magnitudes of 4.9 and 6.5. The lower of the two estimates is only 0.2 unit smaller than the 5.1 magnitude event predicted from the instrumental data. Thus, the instrumental data collected over a 16-yr period could be representative of the seismicity over the past 100 yrs, provided that the Rocky Mountain province relation between area of perceptibility and magnitude is most nearly correct for New Mexico earthquakes. Such knowledge, however, is not certain at this time.

Recent studies of fault scarps by Machette (1980) suggest that the earthquake activity observed from 1962 through 1977 does not represent the general level of seismicity during all of Holocene time (the past 10,000 yrs). Extrapolation of equation (2) indicates that earthquakes capable of producing recognizable fault scarps, that is, shocks with $M_L \geq 7.1$, will occur on the average of once every 10,000 years or longer. Machette (1980) has found evidence for major offsets of Holocene deposits at two locations within the Rio Grande rift. One of these is along the La Jencia fault on the eastern margin of the Magdalena Mountains (approximately 20 km west of Socorro) and the other is along the Cox Ranch fault on the eastern margin of the Organ Mountains (approximately 65 km north of El Paso). Other faults along the Rio Grande rift have reported, but as yet undocumented, Holocene movements.

Another indication of anomalously low seismicity in New Mexico at this time can be obtained from the 1962-1977 instrumental data by comparing the rates of seismic activity in stable and unstable tectonic provinces of New Mexico. The relation between cumulative number of shocks and magnitude for the Colorado Plateau and High Plains combined (exclusive of shocks along the Jemez lineament) is

$$\log_{10}\Sigma N = 2.70 - 0.62\ (\pm 0.025 \text{ s.d.})\ M_L\ (n = 28), \quad (5)$$

whereas for the Rio Grande rift the relation is

$$\log_{10}\Sigma N = 4.81 - 1.35\ (\pm 0.07 \text{ s.d.}) M_L\ (n = 50). \quad (6)$$

For comparative purposes, both earthquake-frequency relations have been normalized to areas of 100,000 sq km. Equations (5) and (6) indicate that earthquakes are more numerous in the Rio Grande rift but that stronger earthquakes are more prevalent in the High Plains-Colorado Plateau.

In New Mexico, with few exceptions, known late Quaternary faulting is restricted to the Rio Grande rift (Seager and Morgan, 1979, fig. 2); thus in the recent geologic past, major earthquakes must have been concentrated in this region. The discrepancy between the geologic evidence of major tectonic movements and the present seismicity suggests that earthquake activity in New Mexico is episodic. Currently the level is low and probably is more controlled by local geologic conditions than by a uniform stress field. Evidence exists for attributing earthquake activity along some sections of the Rio Grande rift to injection of magma (Sanford and others, 1979). Elsewhere in the state the low-level seismicity could be produced by stresses resulting from lateral density variations in the crust (Barrows and Langer, in press), the result of earlier periods of regional tectonism.

An additional indication of relatively low seismicity in New Mexico is obtained by comparing the earthquake-frequency relation for the state with one for southern California. The latter relation is based on 29 yrs of data over an area of 296,100 sq km in the southern part of California (Allen and others, 1965). For comparative purposes, the relations given below for New Mexico (NM) and southern California (SC) have been normalized to 25 yrs and 100,000 sq km:

$$= 3.84 - 0.97\ M_L\ \text{(NM) and} \quad (7)$$

$$= 6.15 - 0.86\ M_L\ \text{(SC).} \quad (8)$$

The difference in levels of seismicity indicated by these equations is very large. For the same time period and area, southern California has approximately 560 times as many shocks of $M_L \geq 4.0$ as New Mexico, and the ratio becomes greater with increasing magnitude. If we assume that NMT magnitudes are, on the average, 0.5 less than the true magnitudes, then the ratio becomes 180, which still indicates that New Mexico has a low level of seismicity relative to southern California.

Relation of seismicity to geology

The evidence available suggests that the present-day low level of seismicity in New Mexico is controlled more by local geologic conditions than by a general stress field. We now turn to a discussion of the local geologic conditions that might be responsible for the observed seismicity in each of the physiographic provinces of New Mexico. The boundaries of these provinces are difficult to define precisely; therefore, the lines drawn in fig. 1 should be considered the approximate location of ill-defined transitional zones between provinces with distinctive tectonic styles. The poorly defined epicenters for shocks that occurred prior to 1962 are plotted on the same figure.

In fig. 3, the instrumentally determined epicenters for the period 1962-1977 are plotted on a shaded relief map of the state. This plot illustrates the relation of seismic activity to large-scale structural features in a manner that does not overemphasize the precision of the epicenters. In a general way, the present relief is an indication of recent tectonic movements—the sharper and larger the relative relief, the more recent the movements.

Rio Grande rift

The Rio Grande rift, passing north-south through central New Mexico (fig. 1), is a major structure formed by east-west crustal extension beginning about 30 million years ago and continuing to very recent times (Chapin and others, 1978).

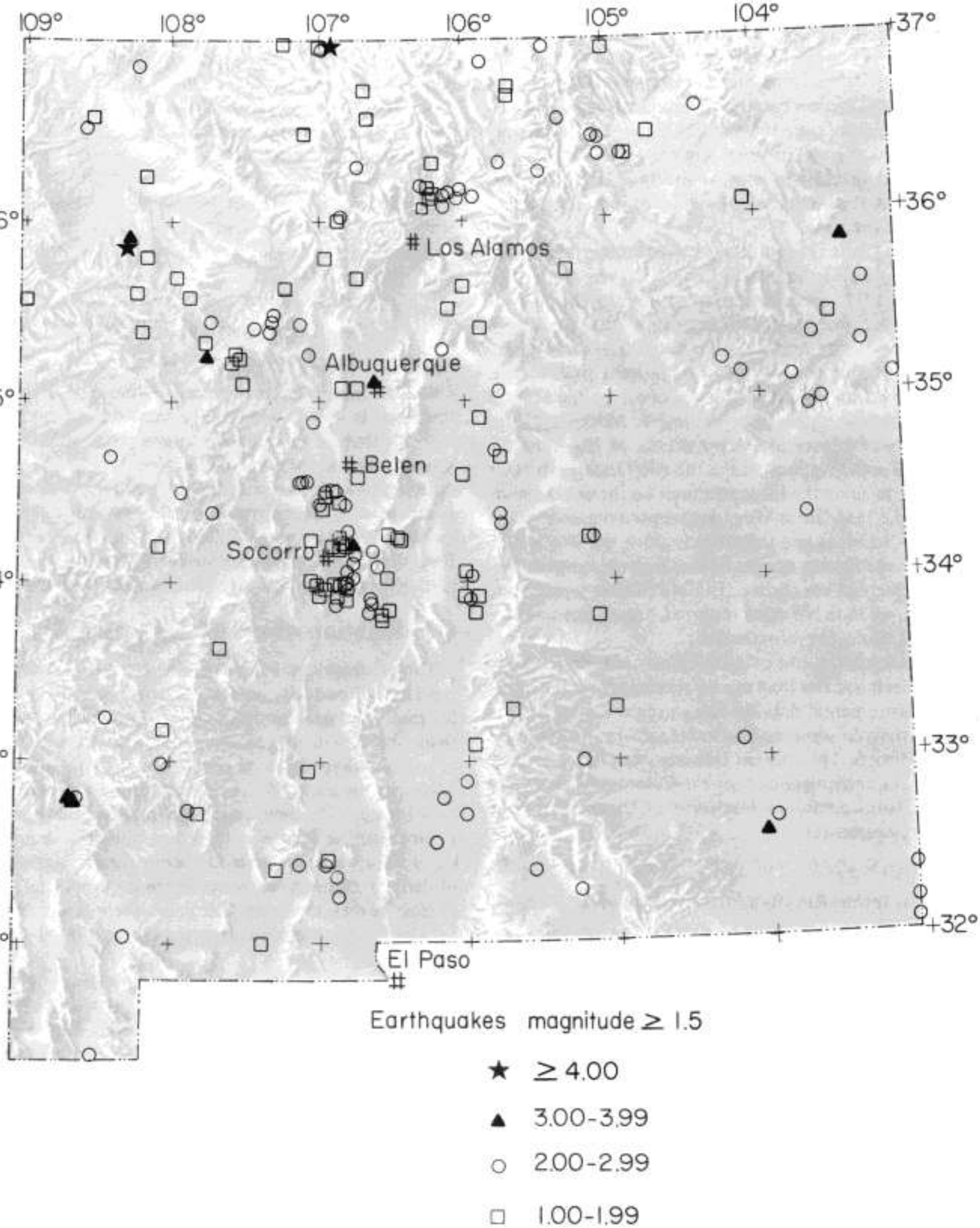

FIGURE 3—INSTRUMENTAL EPICENTERS FOR EARTHQUAKES ($M_L \geq 1.5$) recorded during the period 1962–1977.

The most prominent concentrations of earthquake activity along the rift are between Belen and Socorro and north of Los Alamos (figs. 1 and 3). Common characteristics of the seismicity in both areas are the occurrence of shocks in swarms and a diffuse pattern of seismicity that seems unrelated to major rift-boundary faults (Sanford and others, 1979). The seismic activity in the Socorro area is roughly centered above a thin 1,700-sq-km mid-crustal magma body that has been detected using S-phase reflections from microearthquake seismograms (Sanford and others, 1973; Sanford and others, 1977; Rinehart and others, 1979) and P-phase reflections in deep-crustal profiling (Brown and others, 1979; Brown and others, 1980).

An analysis of first-order level-line surveys in the Socorro area by Reilinger and Oliver (1976) and Reilinger and others (1980) has revealed surface uplift nearly centered on the extensive mid-crustal magma body. The uplift seems to have been continuous since 1912 at an average maximum rate of approximately 5 mm/yr. This observation, in conjunction with the spatial and temporal modes of occurrence of the earthquakes, strongly suggests that the seismicity is arising from crustal stresses created by the injection of magma into the mid-crustal magma body. Preliminary results of a number of different seismic studies using microearthquake sources suggest that intense concentrations of activity in the Socorro area are related to movement of small quantities of magma into the upper crust (Chapin and others, 1978).

The activity north of Los Alamos seems to be closely associated spatially with a pronounced zone of relative subsidence (4.9 cm) discovered through an analysis of level-line data by Reilinger and York (1979). They hypothesized that the depression feature and the earthquake activity in this region are consistent with the deflation of a shallow (approximately 10 km) magma body. Alternately, normal faulting associated with a graben could explain the observations.

Earthquakes elsewhere in the rift may have been generated along faults showing late Quaternary movement (Seager and Morgan, 1979), most likely in the region of intrarift horst-block mountains north of El Paso and along the eastern margin of the rift (approximately 106° W. longitude) between 33.8° N. and 35.0° N. latitude. The possibility of large errors in epicenter locations in these two areas prohibits a positive association with faults active in the late Quaternary. Detailed studies using dense networks of stations will be required to resolve the question.

An interesting featiire of Rio Grande rift seismicity is the presence of large gaps in activity, for example south of Socorro and north of Albuquerque. The seismic gap south of Socorro is particularly interesting in that this area contains evidence of extensive late Quaternary movement along major faults. The existence of these seismic gaps, as well as a level of seismicity no higher than the Colorado Plateau-High Plains provinces, suggests little or no crustal spreading along the rift in recent years. Geodetic measurements across the rift at Socorro (Prescott and others, 1979; Savage and others, in press) are in agreement with this tentative conclusion.

High Plains

The epicenters on the High Plains in the extreme southeast corner of New Mexico (fig. 3) are on the western edge of a large region of seismic activity that extends southward and eastward into Texas; the majority of the earthquakes are centered on the Central Basin platform (Sanford and Toppozada, 1974; Rogers and Malkiel, 1979; Sanford and others, 1980). The Central Basin platform is a major fault-bounded buried structure, approximately 250 km long and 50 km wide, of Early Permian age. The region above this structure is the site of many major oil fields. Because there is no evidence at the surface that the Central Basin platform structure has been rejuvenated in recent geologic time and earthquakes are unknown in the area prior to 1964, some investigators have suggested that the seismic activity is induced by the extraction of oil and/or injection of water for secondary recovery purposes (Shurbet, 1969; Sanford and Toppozada, 1974). Most data support this hypothesis, but conclusive proof is lacking.

The relatively large number of earthquakes in the High Plains of New Mexico between 34.9° N. and 36.1 ° N. latitude (fig. 3) cannot have been induced by production of hydrocarbons because oil fields do not exist in that area. The activity is within and on the flanks of the Tucumcari Basin and along the transition between the Sierra Grande arch and the Amarillo uplift. Earthquakes have been reported along the latter structure through west Texas into southern Oklahoma (Shurbet, 1969).

Jemez lineament

A line of epicenters in the northern High Plains of New Mexico that extends northeastward from 105° W. longitude (fig. 3) may be associated with the Jemez lineament (fig. 1). This structure strikes southwestward from the northeast quadrant of the state across the Rio Grande rift and through the southern part of the Colorado Plateau. The lineament is defined by numerous volcanoes of Pliocene and Pleistocene age, the most prominent of which are the Jemez and Mount Taylor volcanic centers. The section of the lineament northeastward from Mount Taylor is particularly active (Sanford and others, 1979).

Colorado Plateau

The seismic activity on the Colorado Plateau, exclusive of that associated with the Jemez lineament, seems to circumscribe the San Juan Basin (fig. 3). On the eastern margin of the basin, the easternmost line of epicenters could be associated with major north-south faults known from surface and subsurface studies. The San Juan Basin dips steeply westward from these faults and in regions of very high gradients several earthquakes have occurred, including the strongest one in New Mexico during the 1962-1977 period (January 23, 1966, M_L = 4.3).

A northwesterly trend of epicenters extends along the southern margin of the San Juan Basin in the transition zone from the basin to the Zuni uplift. Stratigraphic changes across the transition suggest the possibility that buried faults of Late Pennsylvanian-Early Permian age could be responsible for this activity (Clay Smith, personal communication, 1980). The northeast-southwest alignment of epicenters in the northwest corner of the basin may be associated with faults beneath a known sharp monocline having a similar trend.

Datil-Mogollon volcanic field

Seismic activity in this small province is not great. Numerous faults are known along the eastern and southern margins of the province; but, as elsewhere throughout New Mexico, association of the located earthquakes with specific faults is not possible. In the interior of the province, the few located shocks could have been on unknown fault structures buried beneath a thick blanket of Tertiary volcanic rocks.

Summary

Instrumental data on earthquakes for the period 1962-1977 reveal that the present level of seismicity throughout New Mexico is very much lower than that of southern California. The data also show that shocks are most numerous in the Rio Grande rift, although not so strong as those that occur in the High Plains and Colorado Plateau. The lower intensity for Rio Grande rift shocks is surprising because reports of moderate to strong earthquakes for the period 1849-1962 are mainly from the rift and evidence for late Quaternary and Holocene faulting in New Mexico occurs almost exclusively in the rift.

Instrumental studies of Rio Grande rift seismicity indicate that most earthquakes are not occurring along the major boundary faults and that two long segments of the rift, one with evidence of major late Quaternary faulting, are presently aseismic. These observations, in conjunction with the more or less equal but low level of seismic activity in all physiographic provinces, suggest that the rift and subsequently the entire region is presently under a very low or neutral stress field. For such a stress condition, local geologic factors dictate the occurrence of earthquakes. Consequently, throughout New Mexico earthquake activity is diffuse and has a low intensity everywhere in the state. Holocene movements on major faults within the Rio Grande rift indicate that this condition is not likely to be long term.

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APPENDIX I—MODIFIED MERCALLI INTENSITY SCALE OF 1931 (abridged)

From Abstracts of earthquake reports for the Pacific Coast and western mountain region

I Not felt except by a very few under especially favorable circumstances. (Rossi-Forel scale.)

II Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to III Rossi-Forel scale.)

III Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing truck. Duration estimated. (III Rossi-Forel scale.)

IV During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, and doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably. (IV to V Rossi-Forel scale.)

V Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel scale.)

VI Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII RossiForel scale.)

VII Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well built ordinary structures; considerable in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving motorcars. (VIII Rossi-Forel scale.)

VIII Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed. (VIII + to IX Rossi-Forel scale.)

IX Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX + Rossi-Forel scale.)

X Some well built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. (X Rossi-Forel scale.)

XI Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Typefaces:	Text in 10-pt. English Times, leaded two points References in 8-pt. English Times, leaded one point Display heads in 24-pt. English Times
Presswork:	Miehle Single Color Offset Harris Single Color Offset
Binding:	Saddlestitched with softbound cover
Paper:	Cover on 65-lb. Beckett gray Text on 60-1b. white offset
Ink:	Cover—PMS 553 Text—Black
Press Run:	750